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Global Competitive Sustainability of the Peruvian Asparagus Industry's Agro-Export Performance in the International Market

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Abstract

Peru holds a prominent position in international fresh asparagus trade, with a strong export profile and a well-established presence in global markets. Nevertheless, sustaining this position requires diversification toward a more resilient and sustainable portfolio of destination markets. This study assessed the global competitive sustainability of Peru's asparagus agro-export industry during 2010–2024. Official data from the World Bank, Veritrade, CEPII, and the Peruvian Ministry of Foreign Trade and Tourism (MINCETUR) were analyzed using a quantitative longitudinal single-case study design with descriptive and explanatory components. The results show that the Herfindahl–Hirschman Index (HHI) for Peruvian asparagus exporters remained low, indicating limited firm-level concentration and a relatively diversified supply structure. Thus, Peruvian asparagus exports did not depend on a single dominant firm but were distributed among multiple exporters. In contrast, the HHI for destination markets revealed high geographic concentration of demand. Regarding competitiveness, Peru maintained a strong net-export position, with trade competitiveness index values close to 1. The Revealed Symmetric Comparative Advantage (RSCA) index showed favorable performance in markets such as the United States, Spain, The Netherlands, and the United Kingdom, although this advantage had not yet reached full structural stability. The gravity model, estimated using EGLS with Panel-Corrected Standard Errors (PCSE), identified destination-country economic size as the most important determinant of Peruvian asparagus exports. Geographic distance constrained exports, whereas trade agreements did not show a consistent statistical effect. Potential expansion opportunities were identified in China, Australia, Norway, Ecuador, Sweden, Austria, Russia, Poland, New Zealand, and Romania. Consequently, the competitive sustainability of Peruvian asparagus depends not only on preserving export leadership but also on reducing destination-market concentration, improving logistical efficiency, expanding production capacity, and directing trade policy toward markets with favorable economic fundamentals.

Keywords: market structure; gravity model; trade competitiveness index; revealed comparative advantage index; Herfindahl–Hirschman Index (HHI); Kaplan–Meier method; market potential; asparagus



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1. Introduction

Fresh asparagus has become a high-value product in international agri-food trade because of its nutritional profile, commercial versatility, and ability to serve consumer niches associated with healthy diets, differentiated quality, and a year-round supply of fresh produce. However, this market appeal alone does not guarantee stable and sustainable integration into global markets [1]. For perishable horticultural products, competitiveness also depends on the ability to comply with sanitary standards, maintain efficient transit times and continuity of supply, and adapt to the changing requirements of international buyers [2]. Consequently, the growth of fresh asparagus exports represents an important income-generating opportunity; it also entails substantial risks, particularly when export performance depends on a limited number of markets, highly demanding logistics chains, and a production system already facing substantial environmental and regulatory pressures.

Within this context, Peru holds a prominent position in the international fresh asparagus trade. The Peruvian asparagus industry expanded through market-oriented institutional reforms, free trade agreements with the United States and the European Union, and agroclimatic conditions that enabled year-round production, as noted in [3]. Nevertheless, this export expansion has remained concentrated in a small number of markets, primarily the United States and, to a lesser extent, the European Union. This pattern increases the industry's exposure to shifts in demand, sanitary barriers, and regulatory shocks. In this regard, Ref. [4] shows that the HHI for Peruvian fresh asparagus exports increased from 3929 in 2018 to 4584 in 2022, indicating a clear trend toward dependence on a single destination market. This situation is compounded by competition from Mexico, whose geographical proximity to the US market provides substantial logistical advantages. In 2022, Mexico and Peru accounted for approximately 99% of the volume of fresh asparagus imported by the United States, with Mexico supplying 62% and Peru 37%, according to [5].

The challenge is compounded by the institutional and commercial conditions governing access to international markets. Contemporary agro-export competitiveness depends not only on export volumes or available resources. Exporters must also comply with private standards, phytosanitary requirements, maximum residue limits, and traceability protocols that operate as filters for market entry and continued participation [6]. Similar findings were reported in [7], in which the authors analyzed a panel of 567 Peruvian asparagus-exporting firms between 1993 and 2011. Their study found that private food standards changed firm behavior by increasing vertical integration and modifying supplier relationships. However, these changes did not necessarily translate into improved firm-level export performance. This finding indicates that certification alone does not resolve competitiveness constraints. Sustainable fresh asparagus exports require a broader combination of logistical, organizational, institutional, and commercial capabilities.

The Peruvian agro-export model also faces a serious environmental challenge. Several studies indicate that the expansion of water-intensive export crops, such as asparagus, has contributed to severe water scarcity in the desert areas of Peru's coastal region. Ref. [8] reported that the intensive use of wells for permanent irrigation, primarily for asparagus cultivation in Ica, supports an export industry valued at approximately USD 6 billion annually; however, this production system already faces serious threats related to water availability. Ref. [9] found that 87% of the Ica Valley's blue water footprint originates from groundwater, with 286 mm³ consumed under unsustainable conditions that exceed the aquifer's natural recharge capacity. More recently, Ref. [10] reported that the expansion of large farms producing agro-export crops intensifies groundwater extraction without replenishing the aquifer because drip irrigation does not generate return flows. This process has led to widespread overexploitation of water resources at the regional level. Accordingly,

these conditions constitute a structural sustainability threat that cannot be separated from the analysis of competitiveness.

A primary conceptual foundation for interpreting this issue derives from classical international trade theory. Smith argued that countries benefit by specializing in goods they produce with greater absolute efficiency, whereas Ricardo demonstrated that, even in the absence of such an advantage, a country can benefit from trade by specializing in activities with lower relative opportunity costs. The factor-endowment approach extended this reasoning by proposing that each country's export structure reflects differences in land, labor, and capital. These advantages, however, are insufficient to explain why an export position is maintained or eroded over time. Widely used measures of international agri-food competitiveness, including the Balassa index and its variants, capture only part of the phenomenon and overlook dynamic dimensions such as export learning capacity and innovation [11–13]. Export specialization can foster growth, but it can also intensify trade dependence and constrain market diversification when it is not accompanied by innovation, territorial coordination, and sustainability strategies. This concern becomes particularly important under trade liberalization and regulatory adjustment [14,15]. Moreover, revealed comparative advantage in global agri-food markets varies by product, while subsidies and dependence on differentiated products increase the risk of losing that advantage [16,17]. The technical sophistication of export supply also plays a decisive role in shaping the international positioning of agro-export products. Therefore, export potential depends on both commercial performance and structural factors related to productivity, differentiation, and the persistence of competitive advantage over time [18–20].

Accordingly, the contribution of this study is not establishing that Peru is a successful exporter of fresh asparagus, a fact that is already well documented, but explaining the extent to which this international position can be considered competitive and sustainable when market concentration, export competitiveness, and the stability of export performance over time are examined jointly. The available literature has yet to provide an integrated assessment of Peruvian fresh asparagus that combines these three dimensions for the 2010–2024 period. Nor does it clearly establish whether the product's export leadership rests on a structurally sound foundation or on a more fragile combination of specialization, trade dependence, and environmental pressure. This gap justifies an analysis that extends beyond observed export growth to evaluate the competitive sustainability of Peruvian fresh asparagus in international markets from a broader empirical perspective. Thus, the central research question is as follows: How sustainable was the global competitiveness of the Peruvian asparagus agro-export industry during the 2010–2024 period?

Within this framework, the study assumes that the export performance of Peruvian fresh asparagus should be assessed not only in terms of export growth but also by considering the strength of its competitive position, the structure of its destination markets, and the persistence of that competitiveness over time. Accordingly, this study aimed to assess the global competitive sustainability of the Peruvian asparagus agro-export industry during the 2010–2024 period. Specifically, the study first analyzed the supply-and-demand structure of Peruvian asparagus in international markets; second, it identified export potential in target markets; third, it assessed the competitiveness of Peruvian asparagus exports in international markets; and fourth, it evaluated the stability and duration of Peru's international asparagus trade in relation to international competitiveness.

Restricting the study to a single product and exporting country was a deliberate methodological decision rather than an unacknowledged limitation. The design prioritized analytical depth over comparative breadth, enabling complementary analyses—based on the same census-based empirical dataset, of market structure, trade competitiveness, revealed comparative advantage, temporal persistence, and gravity-based export potential.

A multiproduct design would have reduced the level of methodological detail achievable within the same analytical framework. Accordingly, the research is methodologically framed as a longitudinal single-case study of the Peruvian fresh asparagus agro-export industry rather than as a multi-product or multi-country comparative design.

2. Materials and Methods

2.1. Research Approach, Type, and Design

The study employed a quantitative approach [21] and a non-experimental longitudinal single-case study design because the trade variables were observed in their natural state, without manipulation, over the 2010–2024 period [22]. This was an applied study aimed at generating evidence to support decision-making in Peru's agro-export sector. It combined descriptive and explanatory components, with the latter focused on identifying the determinants of competitiveness and its persistence over time through econometric analysis [23]. The Peruvian fresh asparagus agro-export industry constitutes the bounded case, while annual destination-country export flows from 2010 to 2024 serve as the repeated quantitative observations within that case. This case-study framing defines the scope of inference while remaining fully compatible with the descriptive, survival, and panel-data econometric techniques applied in the analysis.

2.2. Unit of Analysis, Population, and Sample

The unit of analysis was Peru's international trade in fresh asparagus, whereas the unit of observation comprised annual export flows to each destination country during 2010–2024 [24]. The population consisted of all export records for the product classified under Peruvian national tariff subheading 0709.20.00.00, according to the SUNAT tariff nomenclature [25]. Because the study used the full set of available observations for the selected product and period, a census approach covering the full population was used. This approach was appropriate because it enabled the precise calculation of the HHI, RCA, and RSCA indices without selection bias and ensured that the gravity model captured all active bilateral trade relationships during the study period.

2.3. Product Scope and Data Sources

The study focused exclusively on fresh asparagus and excluded frozen, prepared, and preserved asparagus because these product forms exhibit different trade dynamics, distribution channels, and quality standards. Table 1 presents the variables, their definitions, and data sources. Export data, including disaggregated information by exporting firm, destination country, and FOB value, were obtained from Veritrade, a platform that compiles official SUNAT–Customs records [26,27]; origin- and destination-country GDP and destination-country population were obtained from the World Bank [28]; bilateral geographical distance was obtained from CEPII's GeoDist database [29]; and information on free trade agreements in force was obtained from MINCETUR [30].

2.4. Analytical Variables and Indicators

To assess the sustainability of Peru's competitive performance in international fresh asparagus markets, five complementary indicators were calculated: the Herfindahl–Hirschman Index (HHI) of market concentration, the Net Export Index (NEI), Revealed Comparative Advantage (RCA) and its symmetric version (RSCA), the temporal persistence of competitiveness using the Kaplan–Meier estimator, and market potential based on the gravity model [31]. The calculation procedure for each indicator is described in Section 2.5.

Table 1. Variables, definitions, and data sources.

Variable	Variable Definition	Source
Exp	Total Peruvian asparagus exports to the destination country, expressed in current US dollars.	Veritrade
GDP_origin	Gross domestic product (GDP) of the origin country (Peru), expressed in constant US dollars.	World Bank
GDP_destination	Gross domestic product (GDP) of the destination country, expressed in constant US dollars.	World Bank
Pop_dest	Total population of the destination country.	World Bank
Dist	Geographical distance (km) between the capital of Peru and the capital of the destination country.	CEPII (GeoDist database)
FTA	Dummy variable equal to 1 when a free trade agreement (FTA) exists between Peru and the destination country and 0 otherwise.	Peruvian Ministry of Foreign Trade and Tourism (MINCETUR)

Note: GDP = gross domestic product; FTA = free trade agreement; CEPII = Centre d'Études Prospectives et d'Informations Internationales; GeoDist = geographic distance database; MINCETUR = Peruvian Ministry of Foreign Trade and Tourism. The FTA variable is coded as 1 when a free trade agreement between Peru and the destination country is in force and 0 otherwise. Monetary values are expressed in US dollars according to the corresponding data source.

2.5. Procedures

Herfindahl–Hirschman Index (HHI)

The HHI was selected to analyze market structure because it is a widely used and empirically supported indicator in the international economics literature for measuring firm concentration and the geographical diversification of export flows [32]. Unlike simple measures such as the number of destinations or the share of the largest market, the HHI incorporates the complete distribution of market shares, making it sensitive to both the number of destinations and the evenness of their distribution [33]. Its application is particularly relevant to Peruvian fresh asparagus because previous studies have documented increasing concentration in the US market, with the HHI rising from 3929 in 2018 to 4584 in 2022 [34], thereby justifying an assessment of its evolution over the entire 2010–2024 period.

The HHI was originally proposed by Herfindahl (1950) and Hirschman (1945) [35,36] and subsequently became a standard instrument for examining the competitive structure of markets [37]. It is calculated as follows:

$$HHI_t = \sum_{i=1}^n s_{i,t}^2$$

where $s_{i,t} = \frac{X_{i,t}}{\sum_{i=1}^n X_{i,t}}$ represents the share of destination country i in the total value of Peruvian asparagus exports in year t , and n denotes the total number of destination markets. Low index values indicate greater geographical diversification, whereas high values reflect greater concentration and dependence on dominant markets.

The following criteria were used to interpret HHI values.

The US Department of Justice classifies markets into three categories: an HHI below 1500 indicates low concentration; values between 1500 and 2500 indicate moderate concentration; and values above 2500 indicate high concentration [37].

Net Export Index (NEI)

The NEI was included because it allows an assessment of Peru's net position in the international fresh asparagus trade by jointly considering product exports and imports. Unlike the RCA, which considers exports relative to the world average, the NEI identifies

whether a country is a net exporter or net importer of the product and therefore provides a more direct measure of trade competitiveness [38]. Its combined use with the RCA and RSCA allows the evidence on competitiveness to be triangulated from different methodological perspectives, reducing the risk of conclusions biased by the limitations of a single index [39].

$$NEI = \frac{X_{ti} - M_{ti}}{W_{ti}} \times 100$$

where X is the export value of product i in period t , and M is the import value of product i in period t . The NEI ranges from -1 to 1 . A value of -1 indicates that the economy only imports the product, whereas a value of $+1$ indicates that it only exports the product. A value of 0 indicates that exports and imports are balanced at the same level.

Revealed Comparative Advantage (RCA) and Its Symmetric Version (RSCA)

The RCA was selected because it is one of the most widely used indices for identifying products in which a country exhibits favorable export specialization relative to the world average, with more than five decades of empirical applications in agri-food trade [40]. It enables comparisons of the competitive position of Peruvian fresh asparagus both over time and relative to other producing countries and is the reference index used in most studies of Peru's agro-export competitiveness.

However, the RCA has an important statistical asymmetry: it has no defined upper bound and its values are skewed, which complicates comparisons across products and periods [41]. Therefore, the RSCA was adopted as the primary measure because it corrects this asymmetry by bounding the index within the interval $[-1, 1]$ and provides more suitable statistical properties for measuring international specialization [42].

$$RCA_{i,t} = \frac{X_{i,t}^p / X_t^p}{X_{i,t}^w / X_t^w}$$

where $X_{i,t}^p$ denotes Peruvian exports of product i in year t ; X_t^p denotes total Peruvian exports; $X_{i,t}^w$ denotes world exports of product i ; X_t^w denotes total world exports.

RSCA (symmetric version):

$$RSCA_{i,t} = \frac{RCA_{i,t} - 1}{RCA_{i,t} + 1}$$

Positive values indicate revealed comparative advantage, whereas negative values indicate a relative disadvantage [43].

Kaplan–Meier Estimator

The Kaplan–Meier estimator was included because export competitiveness should not be evaluated solely as a static annual snapshot; it is also necessary to examine how long a competitive advantage persists in international markets. This dynamic dimension is crucial for Peruvian fresh asparagus because, as noted in [44], the duration of comparative advantage in agri-food products is heterogeneous and depends on factors such as resource abundance, logistical efficiency, and institutional stability. Survival analysis helps determine whether Peru's export leadership is structurally robust or rests on temporary and fragile conditions, an issue that no static index can reveal [45].

The Kaplan–Meier estimator was selected from among survival-analysis methods because it is nonparametric, requires no assumptions regarding the distribution of survival time, appropriately handles censored observations (markets that continued to receive exports at the end of the study period), and produces readily interpretable visual estimates through the survival curve [46].

$$\hat{S}(t) = \prod_{t_i \leq t} \left(1 - \frac{d_i}{n_i}\right)$$

where $\hat{S}(t)$ represents the estimated survival function, d_i denotes the number of events (export interruption or loss of revealed competitiveness) at time t_i , and n_i denotes the number of trade relationships at risk immediately before t_i . The Peru–destination bilateral relationship was used as the unit of analysis, with observations censored at the end of the study period [47].

International Trade Gravity Model

The gravity model was included because it identifies the structural factors that determine why Peru exports fresh asparagus to certain markets rather than others and estimates the unexploited export potential in each destination. This dimension cannot be captured by competitiveness or concentration indices, which describe what has already occurred but neither explain why it occurred nor project what could occur under different conditions [48].

The gravity model is also a well-established tool for analyzing bilateral trade patterns, with a strong theoretical foundation dating back to Anderson (1979) and Helpman, Melitz, and Rubinstein (2008) [49,50], as well as broad application in studies of Latin American and Peruvian agro-exports [51]. Moreover, it enables market potential to be calculated by comparing model-predicted exports with observed exports, thereby identifying underexploited markets that offer genuine opportunities for geographical diversification. This feature is particularly relevant given the high concentration of Peruvian fresh asparagus exports in the US market [52].

The gravity model is inspired by Newton's (1687) law of universal gravitation, according to which the attraction between two bodies is directly proportional to their mass and inversely proportional to the distance between them. When applied to international trade, economic size (GDP) represents "mass," whereas distance represents trade costs [53]. Tinbergen (1962) first applied the model to bilateral trade [54], providing evidence that trade flows depend on countries' economic size and the distance between them. Anderson and van Wincoop (2003) [55] provided the model with a rigorous microeconomic foundation, and Helpman et al. (2008) [56] extended it to account for zero trade flows.

$$X_{ij} = A \cdot \frac{Y_i^\alpha \cdot Y_j^\beta}{D_{ij}^\gamma}$$

where: X_{ij} represents the value of exports or the trade flow from country i to country j ; Y_i and Y_j are the income levels or gross domestic product (GDP) of countries i and j , respectively; D_{ij} is the geographical distance between the two countries and acts as a trade barrier; A is a constant that captures factors common to all trade relationships (e.g., technology or global trade conditions); and α, β, γ are parameters estimated empirically that reflect the sensitivity of trade to changes in economic size and distance.

To facilitate econometric estimation, Tinbergen transformed the model into its log-linear form:

Estimated Log-Linear Specification

$$\begin{aligned} \ln(\text{EXP}_{ijt}) = & \beta_0 + \beta_1 \ln(\text{GDP}_{it}) + \beta_2 \ln(\text{GDP}_{jt}) + \beta_3 \ln(\text{POP}_{jt}) \\ & + \beta_4 \ln(\text{DIST}_{ij}) + \beta_5 \text{FTA}_{ij} + u_{ij} + \varepsilon_{ijt} \end{aligned}$$

where:

$\ln(\text{EXP}_{ijt})$: natural logarithm of exports from Peru to country j in year t .

$\ln(\text{GDP}_{it})$: natural logarithm of the GDP of the exporting economy (Peru).

$\ln(\text{GDP}_{jt})$: natural logarithm of the GDP of the importing or destination country.

$\ln(\text{POP}_{jt})$: natural logarithm of the destination country's population.

$\ln(\text{DIST}_{ij})$: natural logarithm of the geographical distance (km) between Lima and the capital of the destination country.

FTA_{ij} : dummy variable equal to 1 when a free trade agreement is in force and 0 otherwise.

u_{ij} : unobserved country-specific effect (fixed or random effect).

ε_{ijt} : idiosyncratic error term.

Estimator Selection and Hausman Test

Three specifications were estimated: pooled OLS, which combines all observations without distinguishing between units or periods and is the simplest approach, but it ignores individual heterogeneity [57]; fixed effects (FEs), which control for time-invariant unobserved heterogeneity through country-specific intercepts [58]; and random effects (REs), estimated using EGLS with Swamy–Arora component variances. The RE model assumes that cross-country differences are random and uncorrelated with the explanatory variables and is more efficient when this assumption holds (Table 2) [59].

Table 2. Hausman test.

Test Summary	Chi-Sq. Statistic	Chi-Sq. d.f.	Prob.	
Cross-section random	8.032081	4	0.0904	
Variable	Fixed	Random	Var (Diff.)	Prob.
LN_GDP_ORIGIN	−1.549514	−4.079230	1.22858	0.0225
LN_GDP_DEST	2.248441	4.622404	0.881428	0.0115
LN_POP_DEST	−3.765490	−1.886069	13.598129	0.6103
FTA	−1.963907	−1.368852	0.07778	0.0329

Note: The Hausman test evaluates the null hypothesis that the random-effects model is consistent and efficient relative to the fixed-effects model. Because the overall p -value exceeds 0.05, the null hypothesis is not rejected at the 5% significance level, indicating that the random-effects specification is appropriate for the panel-data model. LN_GDP_ORIGIN = natural logarithm of the GDP of the origin country; LN_GDP_DEST = natural logarithm of the GDP of the destination country; LN_POP_DEST = natural logarithm of the destination-country population; FTA = free trade agreement dummy variable.

The Hausman test was applied to select between the FE and RE specifications. Because the p -value exceeded 0.05, the null hypothesis was not rejected, supporting the random-effects model as the more appropriate specification.

Diagnostic tests revealed heteroskedasticity and contemporaneous correlation across cross-sectional units. To address these problems without changing the estimated coefficients, the model was re-estimated using Panel-Corrected Standard Errors (PCSE) with a period SUR structure, following Beck and Katz (1995) [60]. This procedure provides more robust inference in the presence of problems frequently encountered in bilateral-trade panel data.

Robustness tests were conducted to verify that the findings did not depend on the specific sample or model specification: (i) the model was re-estimated after excluding 2010–2011 to assess possible structural changes, and (ii) an alternative specification excluding destination-country population was tested because this variable had limited statistical significance in the baseline model. In both cases, the main coefficients retained their signs and significance, confirming the robustness of the results [61]. Observations with zero export flows were replaced with a minimum positive constant, allowing the logarithmic transformation to be applied without losing information on newly established trade relationships [56].

Calculation of Market Potential

After estimating the random-effects gravity model, the estimated coefficients were used to project potential exports of Peruvian fresh asparagus to each destination market. Based on the equation estimated in EViews, the $\ln_pred$ variable was constructed to represent the expected logarithmic value of exports for each country and year, based on GDP, population, geographic distance from Peru, and whether a free trade agreement was in force.

Because the predictions are expressed in logarithms, directly converting them to levels introduces systematic retransformation bias. To correct this bias, the smearing estimator proposed in [62] was applied by calculating the mean of the exponentiated model residuals (u_re) as a correction factor (CF). This adjustment provides bias-corrected predictions on the original scale of trade flows and improves the accuracy of the estimated potential exports (Table 3).

Table 3. Classification criteria for export market potential.

Classification	Criterion	Interpretation
Opportunity	Potential > 50	Market with high commercial expansion capacity. Peru exports far below its estimated potential.
Emerging	$10 < \text{Potential} \leq 50$	Market with moderate growth opportunities.
Consolidated	$-10 \leq \text{Potential} \leq 10$	Balanced market; observed trade is consistent with the expected level.
Saturated	Potential < −10	Overexploited market or market with limited room for expansion.

Note: Market potential is expressed as a percentage and compares estimated potential exports with observed exports. Positive values indicate opportunities for commercial expansion; values close to zero reflect a balanced market; and negative values suggest saturation or limited additional growth potential. The classification was constructed using the thresholds defined for the estimated-potential metric.

After applying this adjustment, potential exports were calculated as follows:

$$\widehat{EXP}_{ijt} = e^{\ln(\widehat{EXP}_{ijt})} \times e^{\bar{u}_{ijt}}$$

where $\ln(\widehat{EXP}_{ijt})$ is the logarithmic prediction and $e^{\bar{u}_{ijt}}$ is the smearing correction factor.

Finally, the market-potential metric was constructed by comparing potential exports with observed exports:

$$\text{Potential}_{ijt} = \frac{\widehat{EXP}_{ijt} - EXP_{ijt}}{EXP_{ijt}} \times 100$$

A positive value indicates that Peru exports less than the level predicted by the model for that destination, revealing an unexploited commercial opportunity. A value close to zero indicates that observed trade is consistent with the model's economic fundamentals. Conversely, a negative value indicates a saturated market in which current exports exceed the estimated potential level.

2.6. Data Processing and Statistical Analysis

Data processing combined descriptive statistics, the estimation of trade indicators, and survival analysis. Export records were organized and standardized in Microsoft Excel. Statistical validation, time-series organization, calculation of the HHI and NEI, and Kaplan–Meier survival analysis were performed using IBM SPSS Statistics 27 [63]. The gravity model and panel-data specifications were estimated in EViews [64].

3. Results

3.1. Peruvian Asparagus Export Performance in International Trade

To maintain the manuscript's focus on the analyses and indicators described in the Methods section, the complete series of Peruvian and global asparagus exports and import, including value, volume, the numbers of exporters and importers, and growth rates for 2010–2024. The series shows that Peru's export value increased from USD 290.615 million in 2010 to USD 406.468 million in 2024, whereas export volume decreased from 123,752 to 96,779 metric tons over the same period. Thus, export-value growth was not driven by higher physical volumes but by improved product valuation in international markets. During this period, the number of Peruvian exporters declined from 114 to 82 and the number of importing markets decreased from 42 to 37, reflecting a more concentrated trade structure. Globally, asparagus exports increased from USD 905 million to USD 1.300 billion between 2010 and 2024.

Table 4 shows that Peru and Mexico maintained strong and persistent net-export positions throughout 2010–2024, with values equal or close to 1. Both countries therefore operated primarily as international asparagus suppliers rather than as import-dependent markets. In contrast, the United States, Germany, France, Canada, and Belgium recorded negative values during much of the period, indicating net-import positions or limited export self-sufficiency. Spain, The Netherlands, Italy, and Greece registered moderately positive values, indicating meaningful but less dominant export positions than that of Peru and Mexico. The results show that global asparagus supply was concentrated among countries including Peru, Mexico, Greece, Hungary, Thailand, Ecuador, and Morocco.

Table 4. Net Export Index of the world's leading asparagus exporters.

No.	Exporter	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	Peru	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	Mexico	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3	United States	−0.6	−0.6	−0.5	−0.6	−0.6	−0.7	−0.7	−0.7	−0.6	−0.6	−0.7	−0.7	−0.7	−0.6	−0.7
4	Spain	0.0	0.0	0.0	0.1	0.2	0.3	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.1	0.1
5	The Netherlands	0.0	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.3
6	Italy	−0.1	0.0	0.1	0.2	0.2	0.1	0.3	0.3	0.3	0.2	0.5	0.4	0.3	0.5	0.5
7	Germany	−0.7	−0.6	−0.6	−0.7	−0.6	−0.6	−0.6	−0.6	−0.7	−0.6	−0.6	−0.6	−0.7	−0.6	−0.6
8	France	−0.5	−0.4	−0.4	−0.4	−0.4	−0.3	−0.4	−0.4	−0.4	−0.4	−0.4	−0.3	−0.3	−0.3	−0.3
9	Greece	0.8	0.8	0.8	0.9	0.8	0.8	0.9	0.9	0.9	0.8	0.9	0.9	0.8	0.8	0.8
10	Belgium	−0.5	−0.4	−0.4	−0.4	−0.5	−0.4	−0.4	−0.3	−0.3	−0.2	−0.3	−0.2	−0.4	−0.5	−0.3
11	Canada	−0.9	−0.9	−0.9	−0.9	−0.9	−0.9	−0.9	−0.9	−0.9	−0.8	−0.9	−0.8	−0.8	−0.7	−0.7
12	Hungary	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9
13	Thailand	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0	1.0	1.0	0.9	0.9	1.0	1.0
14	Australia	0.1	0.2	0.1	0.0	−0.1	0.0	0.2	0.1	0.1	0.0	0.0	−0.3	−0.3	−0.2	−0.2
15	Denmark	−0.8	−0.8	−0.9	−0.9	−0.9	−0.9	−0.9	−0.7	−0.6	−0.5	−0.5	−0.7	−0.7	−0.8	−0.5
16	Ecuador	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
17	Morocco	1.0	1.0	0.9	0.9	0.8	0.8	0.6	0.8	0.7	−0.4	0.1	0.8	0.8	0.8	0.9
18	Slovakia	0.3	0.5	0.5	0.5	0.5	0.4	0.3	0.2	0.1	0.1	0.0	0.1	0.2	0.1	0.1
19	Poland	0.9	0.9	0.9	0.8	0.7	0.7	0.5	0.4	0.0	−0.2	−0.3	−0.3	−0.7	−0.7	−0.7
20	Vietnam	−0.2	−0.7	−0.6	0.4	0.5	1.0	0.9	0.2	−0.8	−0.2	−0.4	0.2	−0.6	0.7	0.9
Predominantly Importer														Predominantly Exporter		

Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

A direct comparison between Peru and Mexico, Peru's principal competitor in the US market, shows that both countries maintained a trade competitiveness index close to 1 during 2010–2024, confirming that neither lost its position as a consolidated net exporter. The relevant difference lies not in this indicator but in destination-market structure. Mexico

benefits from geographical proximity to the United States and supplied 62% of that country's imported volume in 2022, compared with Peru's 37%. Peruvian exporters offset this logistical disadvantage through a more dispersed exporting-firm base, as reflected in its low firm-level HHI. This comparison suggests that, relative to Mexico, Peru's competitive sustainability depends more heavily on logistical efficiency and destination diversification than on the strength of its net-export position alone.

3.2. Global Asparagus Market Concentration

Table 5 presents the Herfindahl–Hirschman Index applied to two dimensions of Peruvian asparagus exports: the concentration of Peruvian exporting firms and the concentration of destination markets during 2010–2024.

Table 5. HHI of the supply and demand dimensions of Peruvian asparagus exports.

Year	HHI of Peruvian Exporters	HHI of Destination Markets
2010	382	4233
2011	418	3967
2012	416	4091
2013	495	4110
2014	538	4027
2015	516	4428
2016	526	4286
2017	483	4293
2018	503	3929
2019	426	4228
2020	376	4920
2021	348	4534
2022	408	4585
2023	320	4989
2024	362	4837

Low concentration High concentration

Note: Calculations based on SUNAT records obtained through the Veritrade commercial intelligence platform.

For Peruvian exporting firms, the HHI remained very low throughout the period, ranging from 320 in 2023 to 538 in 2014. The indicator never exceeded the 1500 threshold; therefore, the exporting-firm structure was classified as having low concentration. This result indicates that Peruvian asparagus supply was not dominated by a small number of firms but was distributed across a broad group of exporting firms. From a competitive perspective, this pattern reflects a less concentrated domestic structure in which firm participation is more broadly distributed and dependence on a limited number of exporters is consequently lower.

The temporal pattern also shows a reduction in firm concentration after 2019. The average exporter HHI was approximately 470 during 2010–2019 but declined to about 363 during 2020–2024. This decrease indicates greater relative dispersion of Peru's export supply in recent years. The minimum value of 320 in 2023 supports this interpretation and represents the period's lowest level of firm concentration. Thus, on the domestic supply side, the asparagus export sector displayed a broad competitive structure without pronounced firm dominance.

Destination markets exhibited the opposite pattern. The destination-market HHI remained above 2500 in every year analyzed, ranging from 3929 in 2018 to 4989 in 2023.

Under the methodological criteria adopted, the destination markets for Peruvian asparagus exports were therefore classified as highly concentrated throughout the period. Although the domestic firm-level supply structure was dispersed, Peru's asparagus exports depended on a limited number of international markets.

Geographical concentration has intensified in the most recent years. The destination-market HHI increased from 4233 in 2010 to 4837 in 2024 and reached its period peak of 4989 in 2023. Moreover, the average destination-market HHI increased from approximately 4159 during 2010–2019 to 4773 during 2020–2024. The inclusion of the 2023–2024 observations therefore reinforces the evidence of persistent destination concentration: although the HHI declined from 4989 in 2023 to 4837 in 2024, it remained substantially above both the 2010 level and the threshold for high concentration. This trajectory indicates that dependence on specific international markets became more pronounced toward the end of the study period. In trade terms, the vulnerability of Peruvian asparagus arose primarily from the external concentration of international demand rather than from domestic firm concentration.

Overall, Table 5 reveals an important structural asymmetry: Peru had a dispersed exporting-firm base but highly concentrated international demand across a small number of destinations. This contrast is central to understanding the industry from a strategic perspective. Low concentration among Peruvian exporters reflects a competitive and broad-based domestic structure, whereas high destination-market concentration increases the country's exposure to regulatory, sanitary, logistical, or commercial changes in its principal international markets. Consequently, the competitive sustainability of Peruvian asparagus depends not only on maintaining a broad base of exporting firms but also on achieving greater geographical diversification of destination markets.

Table 6 presents the evolution of the HHI for international asparagus exporters during 2010–2024. Under the criteria established in the Methods section, the aggregate exporter HHI remained within the moderate-concentration range throughout the period, fluctuating between 1843 in 2011 and 2312 in 2017 and never exceeding the 2500 threshold for high concentration. Global asparagus export supply was therefore distributed across several countries, although concentration increased during 2015–2019. The value of 1874 in 2024 confirms that the export market remained moderately concentrated at the end of the period, with no evidence that a single country dominated supply.

The country-level analysis nevertheless reveals substantial heterogeneity. Some exporters recorded values above 2500, indicating highly concentrated destination structures. Mexico reported values close to 10,000 for nearly the entire period, showing that its exports were directed toward very few markets. Canada exhibited a similar pattern, with values at or near 10,000, whereas Greece remained above 7500 in most years. Thus, although the aggregate export market was not highly concentrated, several exporting countries depended heavily on a small number of international destinations.

For Peru, the HHI remained above 2500 in every year analyzed, increasing from 4233 in 2010 to 4838 in 2024 and reaching a maximum of 4989 in 2023. Accordingly, Peruvian asparagus exports were classified as highly concentrated throughout the period. This finding shows that the international position of Peruvian asparagus depended on a limited group of destination markets. Although Peru maintained an important position in global supply, its export structure exhibited risk associated with geographic dependence, particularly after 2020, when index values remained above 4800.

Table 7 presents the HHI for international asparagus importers. Unlike the export market, the aggregate importer HHI showed greater concentration. The index indicated moderate concentration in several years but exceeded 2500 in 2015, 2016, 2017, 2019, and 2020, when international demand was classified as highly concentrated. It reached a maximum of 2738 in 2017 and declined to 2452 in 2024, returning to the moderate-concentration

range. International asparagus demand was therefore not consistently diversified but experienced periods of strong dependence on specific importing markets.

Table 6. HHI of international asparagus exporters.

No.	Exporter	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	Peru	4233	3968	4091	4111	4027	4402	4287	4309	3937	4200	4807	4437	4583	4989	4838
2	Mexico	9802	9889	9979	9981	10000	9980	9983	9974	9988	9999	9999	9999	9999	9998	9999
3	United States	4189	4129	3711	3796	3609	4425	3253	3393	2777	2794	3554	3186	3348	2680	2618
4	Spain	2673	2756	2659	2600	2757	2627	2869	2585	2434	2241	2256	2509	2441	1947	1714
5	The Netherlands	2196	2202	2693	2042	1817	1823	1713	1822	1770	1447	1582	1595	1379	1653	1852
6	Italy	1851	1605	1577	1504	1534	1817	1786	1754	1927	1811	2044	2243	2114	2020	1827
7	Germany	1944	2350	2336	2192	2397	2382	2273	2171	2059	1812	2498	2032	2687	2413	2233
8	France	4493	3760	3311	3997	4785	4364	5296	4813	4487	4225	5629	4690	5596	5079	5481
9	Greece	8363	8892	8557	8327	8422	8769	8673	8769	8602	7731	7654	8210	8557	8079	8326
10	Belgium	1155	1239	1352	1284	1188	1259	1681	1543	1605	1867	1970	2450	1943	2157	1634
11	Canada	9995	10,000	10,000	10,000	9996	9988	10,000	10,000	9966	9828	10,000	9958	9998	9887	10,000
12	Hungary	1799	1699	1745	1840	1683	1692	1596	1832	1949	2415	2360	2506	2654	3087	2302
13	Thailand	4566	3876	3379	1818	1869	1426	1371	1093	1179	842	1166	1392	1114	1215	1095
14	Australia	8111	8004	7764	6563	6430	6109	5691	5625	5747	5433	5719	2957	2077	2425	1918
15	Denmark	8210	8929	7062	8374	6913	6853	6062	4667	4693	4533	4579	4335	4431	3813	4324
16	Ecuador	5281	4938	4913	4781	4318	4762	5594	4239	3959	4085	3259	4176	6393	3961	7875
17	Morocco	7237	6891	9775	9004	10,000	10,000	9907	6666	6074	10,000	10,000	9936	7209	5667	4649
18	Slovakia	4691	5270	5154	4822	4083	4457	4408	4443	4515	4476	3922	4797	4762	4706	4705
19	Poland	7625	7785	6913	6350	5647	4728	4207	4413	4228	7237	7796	4845	1975	1271	1292
20	Vietnam	3312	3000	4700	3271	10,000	3185	3131	4320	5000	3675	4400	5832	3184	7270	5603
HHI		1912	1843	1894	2060	1939	2143	2113	2312	2060	2204	2081	1874	2053	2028	1874
Low concentration																High concentration

Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

Table 7. HHI of international asparagus importers.

No.	Importers	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	United States	4960	4890	4953	4907	5067	5007	4899	4968	4950	4998	4930	4914	4878	4827	4773
2	Germany	2469	2111	1853	1833	1731	1824	1714	1823	1802	1828	2069	1916	2000	1862	1800
3	Spain	7626	8104	7844	7654	7827	8245	6960	6616	5839	6970	6077	6264	6016	6028	5715
4	Canada	3807	3867	3857	3917	3869	4005	4323	4658	4917	5233	5009	5655	5658	5843	6125
5	United Kingdom	5866	6160	5658	5390	5642	6364	6482	6029	6417	6030	5438	5769	5461	4947	4674
6	Switzerland	1516	1535	1365	1420	1647	1876	1826	1870	1778	1965	2502	2177	2177	1917	2212
7	France	3506	3888	3415	3428	3843	4498	4039	3969	3879	3934	4467	5100	5700	5910	5880
8	The Netherlands	7281	7241	6835	6403	6545	6535	4688	3602	3404	2929	3164	3375	3312	1977	1923
9	Japan	2014	2352	2809	2403	3076	3377	3797	4131	4747	5100	6297	7170	7220	6693	6709
10	Belgium	5099	4663	4880	4417	4394	3902	4448	3684	3950	3795	4194	4052	3533	3463	3529
11	Austria	1962	1965	2432	2297	2711	3076	3240	3350	2976	2468	2051	1993	1663	1870	2132
12	Italy	1897	2222	1941	1963	2155	2338	2242	2384	2463	2671	2915	2587	3423	4108	3782
13	Denmark	1881	2440	2325	2084	2118	2563	2433	2346	2757	2109	2719	3638	2281	2429	2440
14	Poland	5984	6532	5671	2484	2393	2707	1794	1725	2066	2095	2328	1895	2330	2696	2107
15	Sweden	3478	3787	2996	2607	2727	2991	2408	2119	1771	1640	1639	1632	1671	1668	2179
16	Australia	3726	3426	3587	4073	4496	5025	5235	6422	5550	7522	9259	9442	9635	9867	9515
17	United Arab Emirates	-	-	3365	3123	3242	2948	2555	2736	2696	2590	2868	2310	2908	3387	2849
18	Norway	5115	4747	4693	5360	4564	4954	4761	4068	3870	4106	3060	3100	3001	2130	2324
19	Singapore	3015	2624	2407	2302	2417	2886	2588	2634	2683	2481	2955	3118	2628	2379	2084
20	Finland	2583	2312	1861	1510	1528	1520	1930	2478	2360	3071	2919	2507	2234	2749	3444
HHI		2241	2181	2027	2464	2208	2540	2534	2738	2448	2642	2577	2225	2480	2434	2452
Low concentration																High concentration

Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

The individual importer analysis confirms this pattern. The United States remained above 4700 throughout the period, indicating a highly concentrated international supply structure. Spain also recorded high values, although these declined from 7626 in 2010 to 5715 in 2024. Canada's concentration increased from 3807 to 6125, while Japan's HHI rose from 2014 in 2010 to 6709 in 2024, shifting from moderate to high concentration. Australia reached 9515 in 2024, indicating extreme dependence on a small number of international suppliers. These patterns may create opportunities for established suppliers but also generate risks during logistical, sanitary, or commercial disruptions.

Conversely, some markets reduced their concentration toward the end of the period. Germany's HHI declined from 2469 in 2010 to 1800 in 2024, remaining within the moderate-concentration range. The Netherlands recorded a more pronounced decline, from 7281 in 2010 to 1923 in 2024, indicating a transition from high to moderate concentration. These results suggest that certain importers diversified their supply sources and reduced dependence on a small number of providers.

Overall, Tables 6 and 7 reveal a structural asymmetry in international asparagus trade. On the supply side, the aggregate exporter HHI remained moderately concentrated throughout the period, although Peru, Mexico, Canada, and Greece displayed highly concentrated individual structures. On the demand side, the aggregate importer HHI alternated between moderate and high concentration, with several major markets depending heavily on a few suppliers. Peru thus competes in a global market whose aggregate supply is not excessively concentrated, while its own exports remain highly dependent on specific destinations. The sector's competitive sustainability therefore requires greater geographical diversification, lower exposure to dominant markets, and a stronger presence in destinations with more diversified supplier structures.

3.3. International Competitiveness of Peruvian Asparagus

Table 8 presents the Revealed Symmetric Comparative Advantage (RSCA) index for Peruvian asparagus exports to the nine leading destination markets during 2010–2024. The results reveal a heterogeneous pattern that reflects both the consolidation of traditional markets and expansion into new destination markets. The Netherlands and the United Kingdom recorded positive and relatively stable values throughout the period, ranging from 0.38 to 0.74 in both cases. These findings confirm that Peru's performance was not merely temporary but reflected a consolidated export position supported by production capabilities, commercial experience, and continued market participation.

Table 8. Revealed symmetric comparative advantage of Peruvian asparagus supply.

Exporter	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
United States	0.55	0.63	0.59	0.53	0.58	0.62	0.57	0.60	0.57	0.67	0.62	0.67	0.66	0.66	0.68
Spain	0.36	0.33	0.22	0.20	0.28	0.28	0.35	0.28	0.35	0.50	0.41	0.46	0.53	0.56	0.60
United Kingdom	0.78	0.79	0.73	0.79	0.75	0.76	0.75	0.73	0.77	0.81	0.79	0.61	0.45	0.60	0.75
The Netherlands	0.74	0.72	0.76	0.64	0.64	0.59	0.56	0.61	0.58	0.51	0.38	0.50	0.55	0.37	0.23
Belgium	−0.65	−0.51	−0.47	−0.25	−0.62	−0.79	−0.52	−0.14	−0.15	0.01	0.12	0.20	0.32	0.43	0.26
Germany	−0.78	−0.74	−0.77	−0.73	−0.64	−0.66	−0.50	−0.69	−0.49	−0.56	−0.76	−0.49	−0.63	−0.56	−0.06
Brazil	−0.65	−0.56	−0.55	−0.64	−0.59	−0.56	−0.57	−0.52	−0.48	−0.46	−0.53	−0.51	−0.59	−0.49	−0.38
Mexico	−0.30	−0.31	−0.47	−0.56	−0.60	−0.60	−0.39	−0.27	−0.20	−0.30	−0.30	−0.44	−0.41	−0.18	−0.24
Ireland	0.32	−0.73	0.36	0.71	0.82	0.83	0.79	0.82	0.79	0.82	−0.41	−0.15	0.51	0.63	0.84
Extreme Disadvantage Extreme Advantage															

Note: Calculations based on SUNAT records obtained through Veritrade and international trade data obtained from the International Trade Centre (ITC) Trade Map.

The stability of the RSCA index for Peruvian asparagus exports was evaluated using cross-sectional regressions that related index values in different base years to those observed in 2024. Stability increased as the reference year approached the final period. For the 2010 base year, the beta coefficient was 0.531 and R^2 was only 0.557, indicating low structural predictability and limited ability of the 2010 competitive position to anticipate that of 2024. As the time horizon shortened, both beta and R^2 increased. The Beta/R ratio did not exceed 1.0 over the shorter horizons, indicating that relative market rankings were maintained but did not become more pronounced. Overall, the results suggest that the symmetric revealed comparative advantage of asparagus had not yet achieved full structural stability.

Table 9 compares the RSCA of the world's leading exporters. Peru displayed the greatest competitive stability, with values close to 0.98–0.99 throughout the period. Mexico also maintained a substantial advantage, although its values declined from 0.85 in 2010 to 0.81 in 2024. Spain and Greece recorded positive but less pronounced advantages, whereas Germany, Canada, Poland, and Denmark showed negative values in several years, indicating an absence of sustained export specialization.

Table 9. Revealed symmetric comparative advantage of global asparagus exports (2010–2024).

No.	Exporter	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	Peru	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.99	0.98	0.98	0.98	0.98
2	Mexico	0.85	0.85	0.83	0.83	0.82	0.82	0.85	0.88	0.86	0.86	0.86	0.86	0.85	0.84	0.81
3	United States	0.25	0.27	0.27	0.21	0.20	0.06	0.10	0.09	0.21	0.16	0.17	0.15	0.16	0.15	0.13
4	Spain	0.46	0.49	0.47	0.48	0.54	0.58	0.48	0.49	0.55	0.53	0.59	0.65	0.66	0.62	0.65
5	The Netherlands	0.30	0.39	0.50	0.46	0.52	0.49	0.45	0.39	0.38	0.33	0.31	0.37	0.33	0.26	0.28
6	Italy	−0.32	−0.27	−0.14	−0.12	−0.12	−0.16	−0.07	−0.13	−0.07	−0.11	0.07	0.20	0.08	0.20	0.16
7	Germany	−0.60	−0.58	−0.57	−0.59	−0.58	−0.62	−0.61	−0.67	−0.66	−0.63	−0.62	−0.51	−0.61	−0.57	−0.45
8	France	−0.31	−0.21	−0.22	−0.17	−0.21	−0.16	−0.21	−0.31	−0.24	−0.22	−0.14	0.04	0.04	−0.06	−0.03
9	Greece	0.92	0.87	0.86	0.84	0.85	0.81	0.82	0.75	0.78	0.67	0.78	0.81	0.76	0.78	0.80
10	Belgium	−0.55	−0.47	−0.43	−0.37	−0.42	−0.38	−0.34	−0.32	−0.26	−0.24	−0.18	−0.09	−0.37	−0.43	−0.21
11	Canada	−0.68	−0.64	−0.59	−0.62	−0.69	−0.71	−0.68	−0.69	−0.65	−0.56	−0.66	−0.60	−0.55	−0.43	−0.36
12	Hungary	0.27	0.13	0.24	0.21	0.21	0.06	0.05	0.00	−0.06	−0.06	−0.09	−0.01	−0.09	0.04	0.21
13	Thailand	0.04	0.11	−0.04	−0.40	−0.38	−0.50	−0.60	−0.58	−0.52	−0.55	−0.60	−0.61	−0.52	−0.31	−0.26
14	Australia	0.11	0.08	0.06	0.03	0.08	0.18	0.21	0.09	0.14	−0.03	−0.12	−0.47	−0.42	−0.47	−0.43
15	Denmark	−0.78	−0.74	−0.92	−0.86	−0.93	−0.91	−0.93	−0.64	−0.39	−0.33	−0.16	−0.22	−0.34	−0.66	−0.07
16	Ecuador	−0.59	−0.77	−0.62	−0.44	−0.48	−0.31	−0.37	−0.41	−0.44	−0.48	−0.17	−0.09	0.02	0.36	0.53
17	Morocco	0.52	0.38	0.07	0.06	−0.41	−0.42	−0.79	−0.56	−0.64	−0.96	−0.91	−0.59	−0.47	−0.32	0.36
18	Slovakia	0.15	0.20	0.16	0.08	−0.04	−0.14	−0.19	−0.24	−0.26	−0.26	−0.40	−0.20	−0.04	−0.24	−0.14
19	Poland	−0.15	−0.05	−0.06	−0.11	−0.05	−0.20	−0.39	−0.51	−0.63	−0.64	−0.67	−0.70	−0.88	−0.83	−0.78
20	Vietnam	−0.96	−1.00	−0.99	−0.98	−1.00	−0.99	−1.00	−1.00	−1.00	−1.00	−1.00	−1.00	−1.00	−0.96	−0.81

Extreme Disadvantage  Extreme Advantage

Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

The stability analysis of the global RSCA index revealed a stronger pattern of structural convergence than that observed for Peru alone. Stability increased as the reference year approached the final period. For the 2010 base year, beta was 0.646 and R^2 was 0.535, indicating moderate structural predictability and limited ability of the 2010 competitive position to anticipate that of 2024. As the horizon shortened, both beta and R^2 increased steadily. The Beta/R ratio remained below 1.0 over the shorter horizons, indicating that exporters' relative rankings persisted without becoming more pronounced. Nevertheless, the global asparagus market had reached a relatively mature configuration in which exporter positions changed little from one year to the next.

Table 10 shows that the normalized relative purchasing capacity for asparagus was concentrated in specific importing markets. The United States recorded stable values of approximately 0.54–0.58, confirming its importance as a persistent demand market. Canada,

Spain, Switzerland, and Denmark also recorded positive values of varying intensity, identifying them as markets with substantial absorption capacity. In contrast, Italy, Poland, Singapore, and the United Arab Emirates recorded negative values, indicating lower relative purchasing capacity or a less favorable position within global demand. The stability of normalized relative purchasing capacity shows clear temporal persistence, particularly in recent years, when beta coefficients and correlations increased. Global asparagus demand was therefore not only concentrated but also characterized by relatively stable trends, reinforcing the need to diversify markets while retaining strong positions in destinations with high purchasing capacity.

Table 10. Normalized relative purchasing capacity of international asparagus demand (2010–2024).

No.	Importers	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	United States	0.54	0.55	0.53	0.58	0.55	0.55	0.55	0.58	0.56	0.57	0.56	0.54	0.56	0.56	0.55
2	Germany	0.13	0.07	0.14	0.09	0.12	0.02	0.04	−0.01	0.04	−0.02	−0.03	0.17	0.05	0.10	0.20
3	Spain	0.26	0.32	0.31	0.25	0.27	0.25	0.29	0.28	0.34	0.31	0.33	0.32	0.36	0.43	0.48
4	Canada	0.43	0.46	0.46	0.41	0.42	0.38	0.36	0.39	0.41	0.39	0.44	0.41	0.42	0.38	0.34
5	United Kingdom	0.02	0.06	0.14	0.19	0.20	0.19	0.14	0.15	0.18	0.14	0.17	0.21	0.19	0.15	0.16
6	Switzerland	0.58	0.59	0.44	0.40	0.47	0.44	0.39	0.38	0.41	0.37	0.38	0.47	0.47	0.47	0.47
7	France	−0.01	−0.02	0.03	0.02	0.04	0.04	0.03	0.00	0.01	0.04	0.10	0.18	0.10	0.06	0.10
8	The Netherlands	0.23	0.25	0.30	0.28	0.26	0.28	0.27	0.26	0.24	0.22	0.20	0.26	0.21	0.10	−0.05
9	Japan	0.18	0.19	0.24	0.07	0.09	0.02	0.11	0.05	0.07	0.02	0.04	−0.05	−0.11	−0.11	−0.14
10	Belgium	−0.17	−0.15	−0.08	−0.06	−0.04	−0.02	0.03	−0.03	−0.04	−0.03	0.07	0.09	0.00	0.05	0.04
11	Austria	0.12	0.04	0.07	0.01	0.03	0.02	0.04	0.02	0.06	0.08	0.05	0.07	0.04	0.14	0.22
12	Italy	−0.38	−0.34	−0.34	−0.38	−0.33	−0.25	−0.40	−0.41	−0.35	−0.33	−0.40	−0.21	−0.35	−0.32	−0.35
13	Denmark	0.07	0.17	0.21	0.05	0.12	0.14	0.10	0.07	0.25	0.18	0.29	0.46	0.35	0.38	0.36
14	Poland	−1.00	−1.00	−0.91	−0.84	−0.80	−0.79	−0.75	−0.77	−0.66	−0.52	−0.56	−0.56	−0.53	−0.31	−0.21
15	Sweden	−0.19	−0.06	0.04	0.10	0.17	0.14	0.05	0.04	0.11	0.10	0.09	0.07	0.13	0.07	0.11
16	Australia	−0.11	−0.15	−0.07	0.01	0.09	0.03	−0.02	−0.01	−0.01	0.01	−0.11	−0.16	−0.10	−0.20	−0.25
17	United Arab Emirates	−1.00	−1.00	−1.00	−1.00	−1.00	−1.00	−0.55	−0.51	−0.43	−0.46	−0.49	−0.54	−0.47	−0.46	−0.47
18	Norway	0.24	0.33	0.39	0.34	0.36	0.31	0.26	0.22	0.18	0.16	0.19	0.20	0.28	0.24	0.22
19	Singapore	−0.65	−0.61	−0.57	−0.59	−0.56	−0.53	−0.52	−0.55	−0.51	−0.50	−0.55	−0.59	−0.52	−0.49	−0.54
20	Finland	−0.32	−0.25	−0.17	−0.17	−0.07	−0.02	−0.02	0.01	0.17	0.07	0.21	0.26	0.19	0.20	0.25

Extreme Disadvantage  Extreme Advantage

Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

The stability analysis of the normalized relative purchasing-capacity index for global asparagus demand during 2010–2024 revealed a highly persistent and statistically significant trajectory. Alpha declined progressively from 10.327 in 2010 to 0.136 in 2023, whereas beta increased from 0.559 to 1.016. This pattern indicates convergence toward greater structural stability, suggesting that the purchasing-capacity pattern reflected sustained market-integration trends rather than temporary market fluctuations. In every year, p -values below 0.001 confirmed the high statistical significance of the estimated relationship. R^2 increased continuously from 0.618 in 2010 to 0.967 in 2023, demonstrating progressively greater explanatory power regarding the persistence of international asparagus competitiveness. The Beta/ R ratio also rose from 0.712 to 1.032, indicating stronger international competitive dynamics and greater resilience to external market changes. Overall, the findings point to increasing maturity and structural stability, with export persistence depending on adaptability, specialization, and the consolidation of international markets.

3.4. Stability and Duration of Peruvian Asparagus Trade in Relation to International Competitiveness

(a) Survival of Peruvian Asparagus-Exporting Firms

The survival analysis shows a progressive decline in the continued participation of Peruvian asparagus-exporting firms in international markets. The estimated survival probability was 95.72% at the end of year 1, 89.69% in year 2, 86.81% in year 3, and 84.66% in year 4. This downward trend continued throughout the study period, reaching 46.4% in year 14. Thus, fewer than half of the firms that initially entered the export market remained active after 14 years.

The Kaplan–Meier curve presented in Figure 1 confirms this sustained decline. By the end of year 2, 10.31% of the firms had exited the export market; the cumulative exit rate increased to 13.19% in year 3, 15.34% in year 4, and 53.6% in year 14. Accordingly, the probability of remaining active in international markets decreased consistently over time.

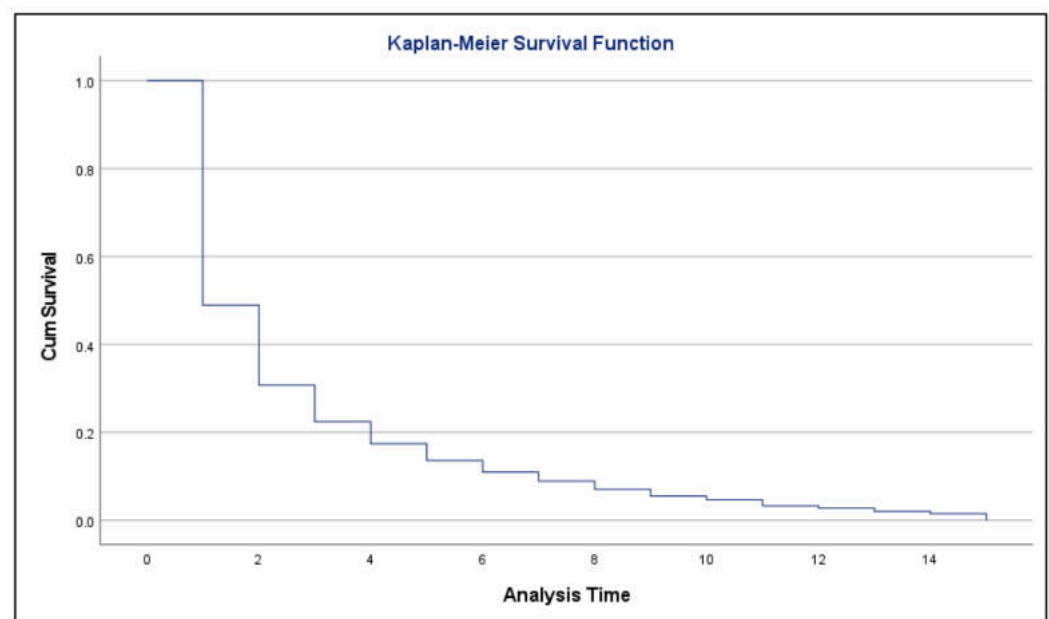


Figure 1. Survival functions of Peruvian asparagus-exporting firms, 2010–2024. Note: Calculations based on SUNAT records obtained through the Veritrade commercial intelligence platform.

The analysis stratified by FOB export value revealed substantial differences between the two groups. Firms with FOB sales below USD 13,498,000 had an estimated mean survival time of 2.046 years (95% CI: 1.870–2.222) and a median survival time of 1 year. In contrast, firms with FOB sales above USD 13,498,000 had an estimated mean survival time of 9.556 years (95% CI: 8.612–10.500) and a median survival time of 9 years (95% CI: 7.902–10.098). These findings indicate that firms with higher FOB sales remained active in international markets for considerably longer periods.

The log-rank (Mantel–Cox) test confirmed a statistically significant difference between the survival curves of the two groups ($\chi^2 = 201.587$, $df = 1$, $p < 0.001$). The null hypothesis of equal survival distributions was therefore rejected. Hence, the survival of Peruvian asparagus-exporting firms with FOB sales below USD 13,498,000 differed significantly from that of firms above this threshold, with the higher-sales group exhibiting substantially greater persistence in international markets.

(b) Survival of Global Asparagus Exporters

The survival analysis shows a progressive decline in the continued participation of global asparagus exporters in international markets. The estimated survival probability

was 93.7% at the end of year 2, 90.7% in year 3, and 84.6% in year 4. This downward trend continued throughout the study period, reaching 51.4% in year 14. Thus, approximately half of the exporters that initially entered the market remained active after 14 years.

The Kaplan–Meier curve presented in Figure 2 confirms this gradual decline. By the end of year 2, 6.3% of exporters had exited the market; the cumulative exit rate increased to 9.3% in year 3, 15.4% in year 4, and 48.6% in year 14. Accordingly, the probability of remaining in international markets decreased over time, although it remained above 50% through year 14.

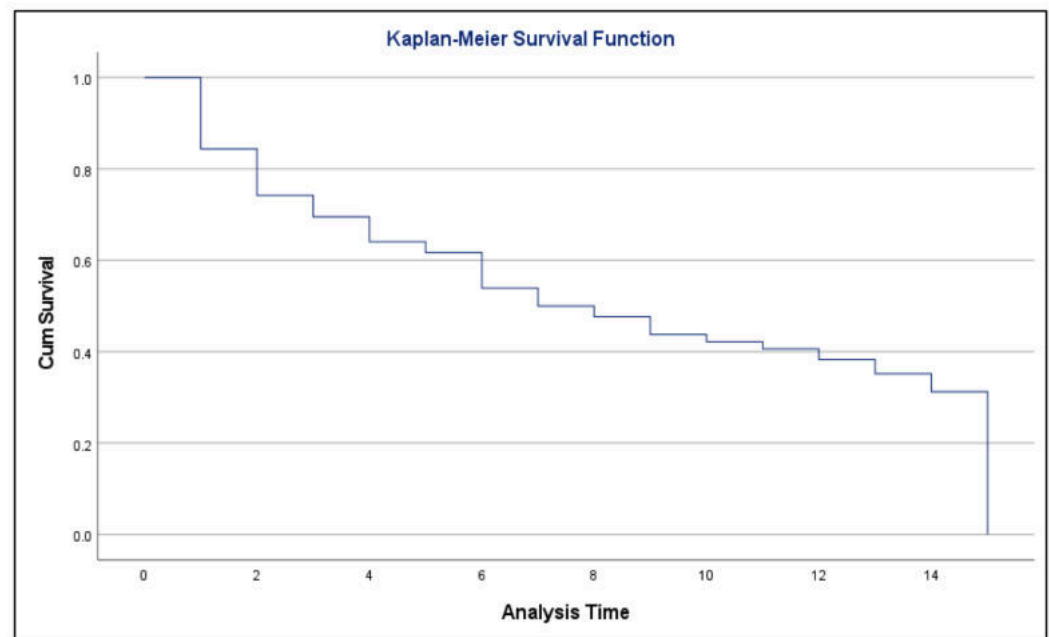


Figure 2. Survival functions of global asparagus exporters, 2010–2024. Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

The analysis stratified by FOB export value revealed substantial differences between the two groups. Exporters with FOB sales below USD 141,885 had an estimated mean survival time of 7.744 years (95% CI: 6.741–8.747) and a median survival time of 6 years (95% CI: 4.233–7.767). In contrast, exporters with FOB sales above USD 141,885 had estimated mean and median survival times of 15 years. These findings indicate that exporters with higher FOB sales remained in international markets for significantly longer periods.

The log-rank (Mantel–Cox) test confirmed a statistically significant difference between the survival curves of the two groups ($\chi^2 = 15.723$, $df = 1$, $p < 0.001$). The null hypothesis of equal survival distributions was therefore rejected. Hence, the survival of global asparagus exporters with FOB sales below USD 141,885 differed significantly from that of exporters with sales above this threshold, with the higher-sales group exhibiting greater persistence in international markets.

(c) Survival of Global Asparagus Importers, 2010–2024

The survival analysis shows a gradual decline in the continued participation of global asparagus importers in international markets. The estimated survival probability was 97.9% at the end of year 2, 96.3% in years 3 and 4, and 94.0% in year 5. This downward trend continued throughout the study period, reaching 68.2% in year 14. Thus, more than two-thirds of the importers that initially entered the market remained active after 14 years.

The Kaplan–Meier curve presented in Figure 3 confirms this gradual decline. By the end of year 2, 2.1% of importers had exited the market; the cumulative exit rate increased to 3.7% in years 3 and 4, 6.0% in year 5, and 31.8% in year 14. Accordingly, the probability

of remaining active in international markets decreased over time, although it remained above 68% through year 14.

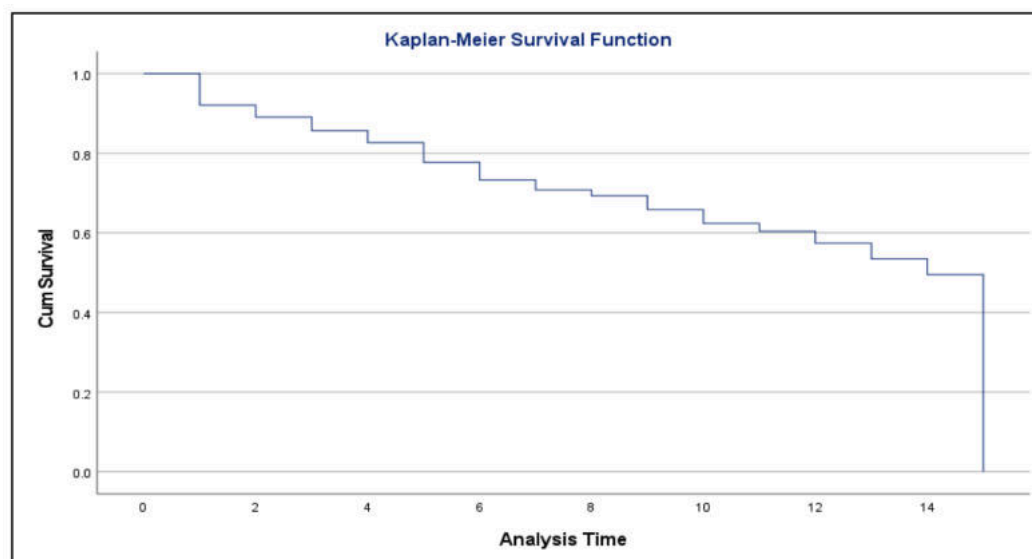


Figure 3. Survival functions of global asparagus importers, 2010–2024. Note: Calculations based on international trade data obtained from the International Trade Centre (ITC) Trade Map.

The analysis stratified by FOB trade value revealed substantial differences between the two groups. Importers with FOB trade values below USD 106,049 had an estimated mean survival time of 11 years (95% CI: 9.771–11.266) and a median survival time of 13 years (95% CI: 11.183–14.817). In contrast, importers with FOB trade values above USD 106,049 had estimated mean and median survival times of 15 years. These findings indicate that importers with higher FOB trade values remained active in international markets for longer periods.

The log-rank (Mantel–Cox) test confirmed a statistically significant difference between the survival curves of the two groups ($\chi^2 = 13.851$, $df = 1$, $p < 0.001$). The null hypothesis of equal survival distributions was therefore rejected. Hence, the survival of global asparagus importers with FOB trade values below USD 106,049 differed significantly from that of importers above this threshold, with the higher-value group exhibiting greater persistence in international markets.

3.5. Opportunities for International Market Diversification Based on the Gravity Model

The gravity model was estimated using EGLS under a random-effects specification to capture unobserved heterogeneity across countries. Diagnostic tests revealed contemporaneous correlation and heteroskedasticity across panel units; therefore, Panel-Corrected Standard Errors (PCSE) were applied. This period-SUR procedure does not change the estimated coefficients but adjusts their standard errors, providing more robust and reliable inference.

The estimated coefficient for Peru's GDP (LN_GDP_ORIGIN) was -7.1702 and was highly significant ($p < 0.001$). Thus, a 1% increase in Peru's GDP was associated with an approximately 7.17% decrease in asparagus exports, indicating high elasticity. The negative sign suggests an inverse relationship between domestic economic expansion and asparagus export performance within this specification. The statistical significance of the coefficient indicates that this relationship was consistent during 2015–2024.

In contrast, destination-country GDP (LN_GDP_DEST) had a positive and significant coefficient of 5.933 ($p < 0.001$), indicating that higher destination-country GDP was associated with greater Peruvian asparagus exports in the model. Destination-country population (LN_POP_DEST) had an estimated coefficient of -3.3314 ($p < 0.001$), indicating a significant

negative association. Together, these findings show that destination-country economic size and population were associated with asparagus exports, although market-specific factors—including preferences, tariffs, and infrastructure—may also be important.

Geographical distance (LN_DIST) had a coefficient of -5.847 ($p < 0.001$). The negative sign is consistent with the theoretical expectation that greater distance reduces trade flows through higher transport costs; the estimate was statistically significant. However, the magnitude may also capture omitted market characteristics or be partially mitigated by logistical conditions and prior agreements.

Regarding overall model performance, the weighted R^2 was 0.118, whereas the unweighted R^2 reached 0.395 (Table 11). The overall F-statistic was 15.345 and statistically significant ($p < 0.001$), indicating that the explanatory variables jointly accounted for variation in exports, although the weighted R^2 remained modest.

Table 11. Results of the gravity model estimated using EGLS with PCSE correction (2015–2024).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	147.2037	48.89940	3.010336	0.0027
LN_GDP_ORIGIN	−7.170244	1.875213	−3.823696	0.0001
LN_GDP_DEST	5.933544	0.749097	7.920925	0.0000
LN_POP_DEST	−3.331439	0.809829	−4.113758	0.0000
LN_DIST	−5.847772	1.298054	−4.505030	0.0000
FTA	−4.077966	1.618218	−2.520035	0.0120
Effects Specification				
			S.D.	Rho
Cross-section random			6.040581	0.5238
Idiosyncratic random			5.759357	0.4762
Weighted Statistics				
R-squared	0.117907	Mean dependent var		1.559526
Adjusted R-squared	0.110224	S.D. dependent var		6.154644
S.E. of regression	5.805550	Sum squared resid		19346.33
F-statistic	15.34506	Durbin–Watson stat		1.090704
Prob (F-statistic)	0.000000			
Unweighted Statistics				
R-squared	0.394765	Mean dependent var		5.402451
Sum squared resid	40,401.32	Durbin–Watson stat		0.522288

Note: Results obtained from the estimation performed in EViews 9.0.

The PCSE correction was essential for addressing heteroskedasticity and contemporaneous correlation across panel sections. The intrasection correlation coefficient of 0.5238 indicated substantial unexplained heterogeneity among destination countries, supporting the use of random effects. The Durbin–Watson statistic ($DW = 0.52$) suggested positive residual autocorrelation, although PCSE reduced the associated inferential bias. Destination-country economic size (LN_GDP_DEST) emerged as the most relevant determinant of Peruvian asparagus exports, whereas trade agreements and other destination attributes showed less consistent effects. These results suggest that strengthening domestic production capacity and logistical efficiency may warrant greater policy attention than negotiating additional trade agreements.

Based on the gravity model, Table 12 shows that observed asparagus exports in 2024 to China, Australia, Norway, Ecuador, Sweden, Austria, Russia, Poland, New Zealand, and Romania were below their model-predicted levels. These markets were therefore classified as “Opportunity” markets. Given the methodological limitation discussed below, however,

these classifications should be interpreted as directional signals of underexploited trade rather than as precise estimates of the magnitude of export potential.

Table 12. Ranking of markets with the greatest expansion potential according to the gravity model (2024).

Destination Country	FOB Exports	Class Code	Classification
China	0.000100	3	Opportunity
Australia	0.000100	3	Opportunity
Norway	0.000100	3	Opportunity
Ecuador	0.000100	3	Opportunity
Sweden	0.000100	3	Opportunity
Austria	0.000100	3	Opportunity
Russian Federation	0.000100	3	Opportunity
Poland	0.000100	3	Opportunity
New Zealand	0.000100	3	Opportunity
Romania	0.000100	3	Opportunity

Note: Results obtained from the estimation performed in EViews 9.0.

The gravity-based estimation of market-expansion potential presented a methodological limitation that prevents direct interpretation. For country–year pairs with no recorded exports ($\text{Export_Fob} = 0$), the original value was replaced with an arbitrary constant (0.0001) before logarithmic transformation. Although this procedure avoids taking the undefined logarithm of zero, the same constant was subsequently used as the comparison base for calculating market potential. Dividing predicted exports (Pred_Exp) by this substitute rather than by an observed export value produced ratios without economic meaning; these were therefore not reported as a results table. Future specifications should either (a) exclude country pairs with $\text{Export_Fob} = 0$ from the potential ratio and report only absolute Pred_Exp values or (b) re-estimate the gravity model using Poisson Pseudo-Maximum Likelihood (PPML), which accommodates zero trade flows without logarithmic transformation or artificial replacement. The available evidence supports only the conclusion that the listed markets received Peruvian asparagus exports below the levels predicted by economic size, population, and geographical distance; the magnitude of the gap cannot be quantified reliably.

4. Discussion

The findings reveal a common structural pattern in the export competitiveness of Peruvian asparagus: a relatively dispersed domestic firm base (HHI of 320–538) coexists with highly concentrated international demand (HHI above 4800 in recent years) and a consolidated net-export position (NEI close to 1). Taken together, these indicators describe a single dynamic rather than separate phenomena. Peru’s export leadership rests on a broad group of firms rather than a few dominant companies, yet most supply is directed to a limited number of destinations, particularly the United States. This integrated interpretation complements the findings of Constantin et al. (2023) [1] and Tibebe et al. (2024) [2], who emphasize that competitiveness in perishable horticultural products depends on standards compliance, continuity of supply, and adaptation to demanding buyers. The decline in exporters and importing markets indicates that the sector operates within a narrower commercial network, potentially constraining long-term sustainability. Consequently, the competitiveness of Peruvian asparagus should be assessed through its productive, commercial, and organizational capabilities.

Beyond confirming previously identified trends in Peru’s export leadership and destination-market concentration [19,65], this study contributes by quantifying the temporal persistence of competitiveness through Kaplan–Meier analysis and RSCA stability

regressions, an approach not previously applied to Peruvian fresh asparagus. Beta and R^2 increased from 0.531 and 0.557 for the 2010 base year to values close to 1 in recent years, providing new empirical evidence of increasing structural stability that cannot be inferred from descriptive export data or prior studies alone.

The NEI results show that Peru maintained a persistent net-export position throughout the study period, with values close to 1. Peru therefore consistently operated as an international supplier rather than as an importer. This result is consistent with the findings of Escalante Yaulilahua et al. (2023) [65], who attribute Peruvian competitiveness to favorable agroclimatic conditions, trade-liberalization reforms, and production capacity.

Nevertheless, Mexico's equally strong position demonstrates that Peru's leadership operates within a highly demanding competitive environment. Peru's commercial strength must therefore be sustained through logistical efficiency, quality, and market diversification.

The HHI for Peruvian exporters indicates low firm concentration, with values between 320 and 538. Exports thus depended on a broad group of firms rather than on a single dominant company. Consistent with the studies by Cadot et al. (2011) [33] and Sangita (2018) [32], such dispersion can reduce vulnerability associated with firm concentration. However, the total number of exporters declined from 114 to 82 between 2010 and 2024. Although concentration remained relatively low, declining participation may signal reduced competitive breadth unless firms' capacity to remain in export markets is strengthened.

Destination-market HHI results revealed a different pattern, with recent values remaining above 3900 and indicating high geographical concentration, particularly in traditional markets. This finding is consistent with that of Almerco et al. (2022) [66] and with that of Gutiérrez Chacón and Machuca (2019) [67], who argue that sustained destination diversification reduces volatility and improves export stability. Thus, a relatively dispersed firm base directs much of its supply to a few markets, increasing exposure to commercial, sanitary, and logistical shocks.

The international HHI comparison shows that concentration is not exclusive to Peru. Mexico also displayed a concentrated destination structure, whereas Spain and The Netherlands became more diversified toward the end of the period. Peru's position was therefore competitive but less balanced than that of some European competitors. This interpretation is consistent with the results of Pablo et al. (2014) [68], who argue that Peruvian asparagus competitiveness is not expressed uniformly across the global market but remains oriented toward specific destinations. Maintaining leadership therefore requires destination expansion and reduced dependence on traditional markets.

The persistent concentration of international demand confirms the central importance of the United States for fresh asparagus. This result is related to the findings of Khanal et al. (2024) [5], who show that Mexico and Peru jointly accounted for most US fresh asparagus imports in 2022, while Mexico benefited from a substantial logistical advantage. Peru consequently maintained a clear commercial position but faced a significant geographic and logistical disadvantage. Its competitiveness depends not only on producing high-quality asparagus but also on reducing transit times, logistics costs, and associated risks.

RSCA results for the main destinations show uneven competitiveness across markets. The Netherlands, the United Kingdom, and the United States recorded positive values, indicating revealed comparative advantage in markets where Peruvian asparagus had built market experience and established positions. This finding is consistent with the observations of Laursen (2015) [41], who emphasizes that RSCA provides a more stable measure of international specialization by correcting the asymmetry of the Balassa index. Conversely, negative values in Germany, Brazil, and Mexico indicate that Peru's performance was not uniform. Its advantages were therefore destination-specific and did not guarantee equally strong competitiveness across all global markets.

The international RSCA comparison shows that Peru had a very high degree of specialization in asparagus. Values close to 0.98–0.99 throughout the period indicate a strong position relative to competitors. This finding is consistent with research by Worku et al. (2024) [69], who identify revealed comparative advantage and Porter’s Diamond Model as useful tools for analyzing agri-food competitiveness. However, a strong index should not be interpreted as competitive self-sufficiency: no single indicator explains the sector’s overall sustainability. Peru combined specialization with a continuing need for diversification, firm survival, and territorial sustainability.

Export-volume segmentation revealed a substantial difference between firms with lower and higher sales. Firms with higher export values had longer survival times, whereas firms with lower FOB values faced a greater risk of early market exit. This result is consistent with research by Schuster and Maertens (2015) [7], who show that private standards reshape firm organization and may raise entry and survival barriers for actors with limited technical or financial capacity. Sector sustainability therefore requires not only increasing sales but also strengthening lower-capacity firms so that they are not excluded from high-value commercial environments.

Survival among global exporters declined over time, demonstrating that market exit is an inherent feature of international trade. Compared with the Peruvian case, global exporters showed greater persistence in the later intervals. Peru maintained an important trade advantage but faced challenges in sustaining its firm base. This interpretation is consistent with the results of Bojnec and Fertő (2017) [70], who argue that competitive persistence varies according to resources, export orientation, and structural conditions. Sustainable competitiveness in Peruvian asparagus therefore requires firm-strengthening policies in addition to trade-promotion strategies.

The EGLS gravity model with PCSE correction produced coefficients consistent with the expected theoretical direction: destination-country economic size (LN_GDP_DEST) was positively associated with Peruvian asparagus exports, whereas geographic distance (LN_DIST) was negatively associated with them. These results are consistent with those of Anderson and van Wincoop (2003) [55], Helpman et al. (2008) [56], and Mejía and Hassan (2017) [51]. Nevertheless, the model’s limited fit requires caution: the weighted R^2 of 0.11 and unweighted R^2 of 0.39 show that a substantial share of export variation remained unexplained. Rather than invalidating the exercise, this limited explanatory power suggests that market entry also depends on factors excluded from the standard gravity specification, including maximum residue limits, private certification, port logistics efficiency, and supply constraints such as irrigation-water availability, not only destination-country economic size, population, and distance.

The commercial competitiveness documented in this study represents only one dimension of the sustainability invoked in its title. Previous research shows that approximately 87% of the blue water footprint of the Ica Valley is supplied by groundwater extracted above its recharge rate [8,9] and that the expansion of export-oriented cultivation has intensified this overexploitation [10]. Access to markets with higher RSCA values is also mediated by private standards and certifications that affect exporters’ continued participation [6,7]. Neither the water-use and environmental-certification dimensions nor the carbon footprint associated with transporting a highly perishable product was included as an explanatory variable in the estimated models. Therefore, the HHI, NEI, RSCA, and gravity-model results describe robust commercial competitiveness but cannot, by themselves, establish that such competitiveness is environmentally sustainable over the medium term. The commercial and environmental dimensions should be interpreted as complementary rather than interchangeable.

The integrated evidence from the five indicators shows that Peruvian asparagus had consolidated commercial competitiveness and a broad firm base but remained geographically concentrated. The gravity model confirmed the importance of economic size but did not explain most of the observed variation, while the environmental dimension remained beyond the model's empirical scope. The sector's competitive sustainability therefore depends not only on maintaining export leadership and diversifying destinations but also on integrating logistical efficiency, environmental certification, and water availability into sectoral policy and future research as considerations alongside destination-market size.

5. Conclusions

During 2010–2024, Peruvian asparagus maintained a persistent net-export position (NEI close to 1) and a high, stable revealed symmetric comparative advantage (RSCA close to 0.98–0.99). Export value increased from USD 290.615 million to USD 406.468 million despite a decline in physical volume from 123,752 to 96,779 metric tons. This combination confirms improved product valuation; however, the decline in exporters (from 114 to 82) and importing markets (from 42 to 37) indicates a narrower commercial network than at the beginning of the period.

The market structure showed a clear asymmetry. The HHI of Peruvian exporters remained low, indicating a diversified firm-level supply structure, whereas the destination-market HHI remained above 3900 and reached 4989 in 2023, reflecting persistent geographical concentration, primarily in the United States. Survival analysis confirmed that this structure entails differentiated risks: firms with higher FOB values remained in the export business significantly longer than smaller firms.

The EGLS gravity model with PCSE correction confirmed that destination-country economic size was the most relevant determinant of Peruvian asparagus exports, whereas geographical distance imposed a significant constraint, and trade agreements showed no consistent effect. Nevertheless, the model's limited explanatory power (weighted $R^2 = 0.118$) and the methodological limitation in the market-potential indicator mean that China, Australia, Norway, Ecuador, Sweden, Austria, Russia, Poland, New Zealand, and Romania should be interpreted as directional signals of underexploited trade rather than as definitive numerical estimates of the magnitude of potential.

Overall, the competitive sustainability of Peruvian asparagus depends not only on maintaining export leadership but also on reducing destination concentration, strengthening the survival of smaller firms, and incorporating environmental dimensions such as water use, certification, and carbon footprint into future models.

6. Study Limitations and Future Research

The study was methodologically limited to a single product, fresh asparagus. Previous research indicates that aggregating products with different trade dynamics, phytosanitary standards, and price structures produces competitiveness indices that are not representative of any individual product [40], whereas multiproduct or multicountry comparative designs tend to sacrifice methodological depth for descriptive breadth [11,12]. Nevertheless, the analytical depth achieved for asparagus limits the generalizability of the findings to other agro-export products or producing countries. The conclusions should therefore be interpreted as evidence specific to Peruvian fresh asparagus rather than as a pattern necessarily applicable to fruit and vegetable agro-exports more broadly. This bounded single-case study design intentionally prioritizes analytical depth within the Peruvian asparagus sector and does not seek statistical generalization beyond the case.

The empirical design focused on market structure, trade competitiveness, and temporal stability indicators without incorporating quantitative environmental variables. The

results therefore provide evidence on the persistence and structure of the commercial competitiveness of Peruvian asparagus, whereas environmental sustainability serves primarily as a conceptual framework rather than an empirically modeled component. Future research should integrate quantitative environmental indicators, including the blue water footprint documented in [9], as additional explanatory variables in the gravity model so that commercial and environmental sustainability can be evaluated jointly.

Finally, the single-product focus limits direct generalization to other agro-export contexts. Nevertheless, the study offers an integrated methodological framework that can be replicated for other highly specialized agri-food products, including avocados, blueberries, table grapes, and mangoes. The framework combines market structure, trade competitiveness, temporal persistence, and gravity-based potential indicators within a single analytical design. Its value therefore lies less in statistical generalization than in validating an integrative methodology applicable to other sector-specific cases in Latin American agro-exports.

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